

Observations of geomagnetic cutoff variations during solar energetic particle events and implications for the radiation environment at the Space Station

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Abstract. Data from the polar-orbiting Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) satellite have been used to measure the location of the geomagnetic cutoff for low-energy protons and alpha particles during several large solar energetic particle events from mid-1992 to late 1998. When fluxes are sufficiently high, the cutoff latitude can be measured up to four times per orbit, allowing the variability of the cutoff to be observed on relatively short timescales. We find significant changes in the cutoff location, often by more than 5° in less than 1 day, and these changes are well correlated with geomagnetic activity as measured by either *Dst* or *Kp*. Spacecraft in intermediate-inclination orbits such as the International Space Station (ISS) graze the geomagnetic polar cap at certain longitudes each day. Calculations show that a 5° suppression in the average geomagnetic cutoff increases by more than a factor of 2.5 the time that the ISS spends in the polar cap exposed to energetic particles. Since the Station is only vulnerable at certain longitudes, however, real-time monitoring of the cutoff location from a polar-orbiting spacecraft could be used to provide advance notice of the polar cap location and conditions, sometimes hours before the Space Station itself reaches high magnetic latitudes.

1. Introduction

The onset of a new cycle of solar activity has brought with it a renewed interest in the effects of the corresponding space weather activity on technology. On the ground, power grids are subject to geomagnetically induced current surges, which may lead to power outages, while induced currents in pipelines can accelerate their corrosion. In orbit, satellites are directly subjected to energetic electrons, protons, and heavier ions, which can produce errors or failures due to deep dielectric charging, differential spacecraft charging, and single event upsets. For a recent review of space weather consequences, see *Feynman and Gabriel* [2000, and references therein].

The impact of the present solar maximum on space weather has taken on an added significance since it coincides with the construction of the International Space Station (ISS), which is expected to require roughly 1500 hours of astronaut extravehicular activity over the next

4 years to complete. With this schedule, recent calculations find that it is very likely that at least two ISS construction missions will be underway during a major solar particle event and indicate a better than 50% chance of a significant radiation dose acquired during as many as five missions [*Siscoe et al.*, 2000]. Developing the ability to characterize and accurately predict the radiation environment at the Space Station is thus of considerable interest to the astronaut community.

During large solar energetic particle (SEP) events, the radiation dose received by a low-altitude Earth-orbiting satellite depends not only on the intensity of the particle event but also on the inclination of the orbit, since the geomagnetic field effectively shields low latitudes from these relatively low energy particles. At intermediate inclinations, spacecraft such as the ISS do not entirely avoid the geomagnetic polar cap but rather graze it at certain longitudes each day. During geomagnetic cutoff suppressions, when the size of the polar region increases, such spacecraft will experience a significant increase in potential radiation exposure compared with geomagnetically quiet times.

In this paper we present measurements of the variability in the location of the geomagnetic cosmic ray

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Paper number 2000JA000212.

0148-0227/01/2000JA000212\$12.00

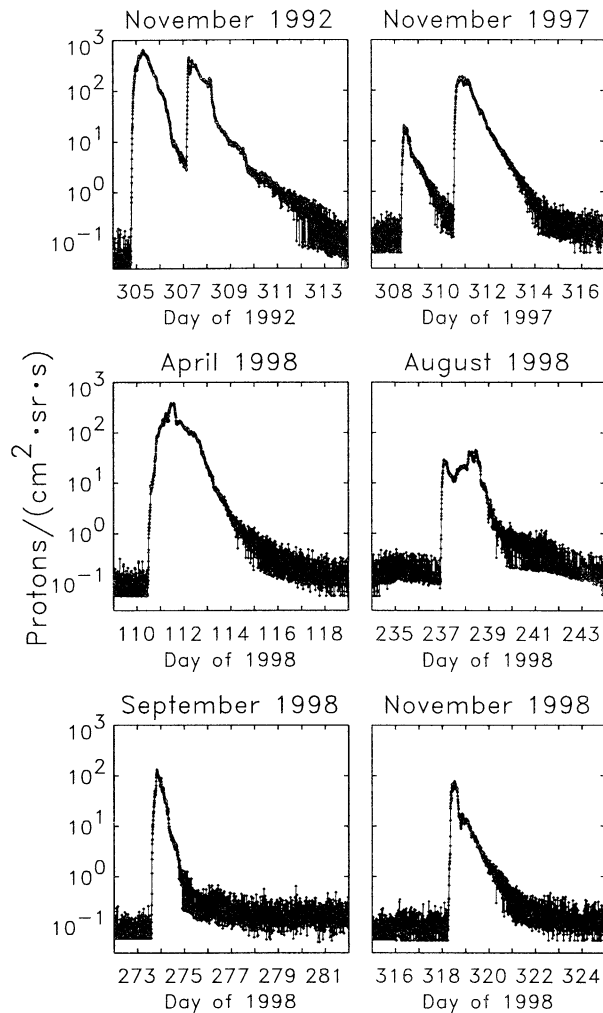


Figure 1. Time profiles of the intensity of > 30 MeV protons from the GOES 7 and 8 satellites during the solar energetic particle (SEP) event time periods examined here.

cutoff during the six time periods of large solar energetic particle events from October 1992 through November 1998 shown in Figure 1. We illustrate the correlation of the cutoff location with geomagnetic activity, and we describe the effects of the size of the polar region on the radiation dose at the orbit of the ISS. We also discuss the possibility of real-time monitoring of the location of the cutoff and the radiation environment in the polar region. An earlier version of part of this work was presented by Leske *et al.* [1997].

2. Data Analysis

The measurements reported here were made from the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) spacecraft, which was launched into a 520×670 km 82° inclination orbit in July 1992 [Baker *et al.*, 1993]. In particular, data from two silicon solid state detector instruments aboard SAMPEX, the Mass Spectrometer Telescope (MAST) [Cook *et al.*, 1993a]

and the Proton/Electron Telescope (PET) [Cook *et al.*, 1993b], were used.

Figure 2 illustrates the 20–29 MeV proton rate from PET for a single pass over the north polar cap during the 1992 SEP events plotted versus invariant latitude. (The invariant latitude, Λ , is the magnetic latitude at which a given field line intersects the Earth's surface and is related to the magnetic L shell by $\cos^2 \Lambda = 1/L$; see, e.g., Roederer [1970]. Throughout this paper, unless otherwise specified, the invariant latitude is calculated from the SAMPEX orbital ephemeris using the International Geomagnetic Reference Field (IGRF) 1990 magnetic field model.) The transition between the regions where these low-energy particles have access to the SAMPEX orbit at polar latitudes and where they are completely excluded by the geomagnetic field at low latitudes is easily detected. We define the cutoff location to be that invariant latitude at which the count rate is half of its mean value above 70° . We were able to measure this cutoff to an accuracy of $\sim 0.2^\circ$ four times per orbit (at each polar cap entrance and exit) for several proton and alpha particle counting rates whenever the rates were high enough to easily do so during the six periods shown in Figure 1.

Nominally, SAMPEX is zenith pointing at high latitudes; however, during portions of the mission the spacecraft was spun at one revolution per minute to facilitate studies of the pitch angle distributions of magnetospheric particle populations. During these 1 rpm spin periods, the count rates at high latitudes are highly modulated, varying from full intensity to near zero in-

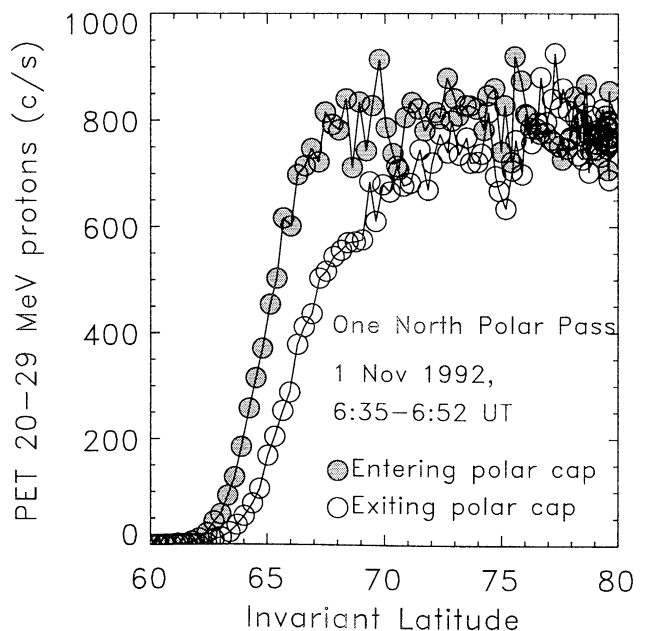


Figure 2. Rate of ~ 20 –29 MeV protons from the Proton/Electron Telescope (PET) measured every 6 s plotted versus invariant latitude for a single passage into (filled circles) and out of (open circles) the north polar region.

tensity every 30 s as the spacecraft turns from zenith pointing to Earth pointing. This modulation greatly complicates the identification of the cutoff edge shown in Figure 2. For this reason, portions of high count rate intervals during these six periods, namely the first of the two SEP events in November 1997 and the onsets of the second November 1997 and the April 1998 events, were omitted from our analysis.

Several SAMPEX particle rates were examined for some of the SEP events. These rates include the PET PLO rate (which responds primarily to ~ 20 – 29 MeV protons) and PHI rate (29 – 64 MeV protons) and the MAST Z1 rate (~ 10 MeV protons) and Z2 rate (8 – 15 MeV/nucleon He). It was found that the PLO rate occasionally showed signs of contamination by outer-zone electrons in the radiation belts just equatorward of the cutoff boundary we were trying to measure, thus complicating the analysis. The PHI rate, while typically free of such contamination, was often very low owing to the lower proton fluxes at high energies combined with the relatively small geometry factor (~ 1.7 cm²·sr) of the PET instrument, which limited the time periods available for analysis. Since the MAST rates were for lower-energy particles and the MAST geometry factor is larger (~ 8 cm²·sr for He), the MAST count rates were always higher than the PET rates. Of the two MAST rates examined, we mainly concentrate on the higher rigidity Z2 rate.

3. Observations

From earlier studies, such as those of precipitating electrons [e.g., *Gussenhoven et al.*, 1983], the poleward boundaries of the outer-zone electrons [e.g., *Kanekal et al.*, 1998], or numerous studies of the aurora [e.g., *Whalen et al.*, 1985, and references therein], it is known that the boundaries of the regions where energetic particles are found at high latitudes depend on both geomagnetic activity and local time. Since the SAMPEX orbit precesses from dawn-dusk to noon-midnight and back in ~ 3 months and we are studying only six SEP periods, each of which lasts at most several days, the cutoff crossings we measure are not very uniformly distributed in local time, with some local times very poorly sampled. Therefore, rather than examine the cutoff location selected for both geomagnetic activity level and local time separately, we instead consider first the effect of geomagnetic activity on the orbit-averaged cutoffs; then the effect of local time on the individual cutoffs after correcting for geomagnetic activity. As indicators of geomagnetic activity, we consider both *Dst* and *Kp*, both of which are readily available or forecast in near real time and therefore potentially of interest as a proxy for the cutoff measurements.

3.1. Cutoff Variations With Geomagnetic Activity

Orbit-averaged geomagnetic cutoffs during the six time periods examined here are shown in Figures 3

and 4 as a function of time. Significant variations in the cutoff location, often by $\sim 5^\circ$ – 10° in less than a day, are clearly seen. Note that for the November 1992 and November 1997 periods we show the cutoffs derived from several different rates and that the shapes of the curves from the different rates agree with each other extremely well. Since the rates correspond to different rigidity particles and since higher rigidity particles penetrate to lower latitudes, small offsets have been added to the curves for different rates, as indicated, to better illustrate the similarity in overall shape. Further discussion and additional SAMPEX measurements of the rigidity dependence of the cutoff latitude for heavy ions are given by *Leske et al.* [1996] and *Ogliore and Mewaldt* [1999].

Also shown in Figure 3 is the geomagnetic activity index *Dst* during the same time intervals. Here we have plotted each *Dst* value at the center of the 1-hour time interval over which it was measured, and we have scaled it linearly to compare to cutoff invariant latitude. In general, the shapes of the time variations in the cutoff are remarkably well correlated with corresponding changes in *Dst*, even down to small amplitudes ($\lesssim 1^\circ$) and short (several hour) timescales. There are places, however, where significant differences exist. For example, the shapes of the two curves are quite different on day 312 of 1997. From the standpoint of assessing radiation hazards in the polar regions, it is important to know when the size of the polar cap suddenly increases. Unfortunately, we find that the cutoff suppression actually leads the corresponding change in *Dst* by nearly half a day on day 306 of 1992, and perhaps to a lesser extent on day 113 of 1998, suggesting that *Dst* is an unreliable indicator of cutoff suppressions during the most critical periods.

Since during a geomagnetic storm, *Kp* often responds before *Dst*, it may be that the sudden cutoff suppressions are better correlated with *Kp*. Figure 4 is the same as Figure 3, only here the cutoffs are compared to *Kp*, which is plotted at the center of the 3-hour window during which it was measured. It appears that *Kp* tracks the cutoffs on day 312 of 1997 and day 306 of 1992 better than *Dst*. However, *Kp* appears to lead the cutoff suppressions on days 113 and 238 of 1998 and is discrepant at other times as well. Also, the coarser resolution of *Kp* (only 28 possible levels) and coarser temporal resolution of 3 hours mean that many small-scale features (e.g., the “spike” on day 238 of 1998) seem less well fit than by *Dst*, if they are seen at all.

Interpolating the geomagnetic index measurements to the times of the cutoff measurements yields the correlation plots shown in Figure 5 for *Dst* and Figure 6 for *Kp*. In both cases, orbit-averaged cutoffs are once again being used. The degree of correlation between the cutoff location and either *Dst* or *Kp* is very similar, with a correlation coefficient of 0.76 for the former and -0.77 for the latter. At any given value of *Dst* or *Kp*, there is a spread of $\sim 2^\circ$ – 3° in the corresponding orbit-averaged cutoff latitude. A change in *Dst* by 200

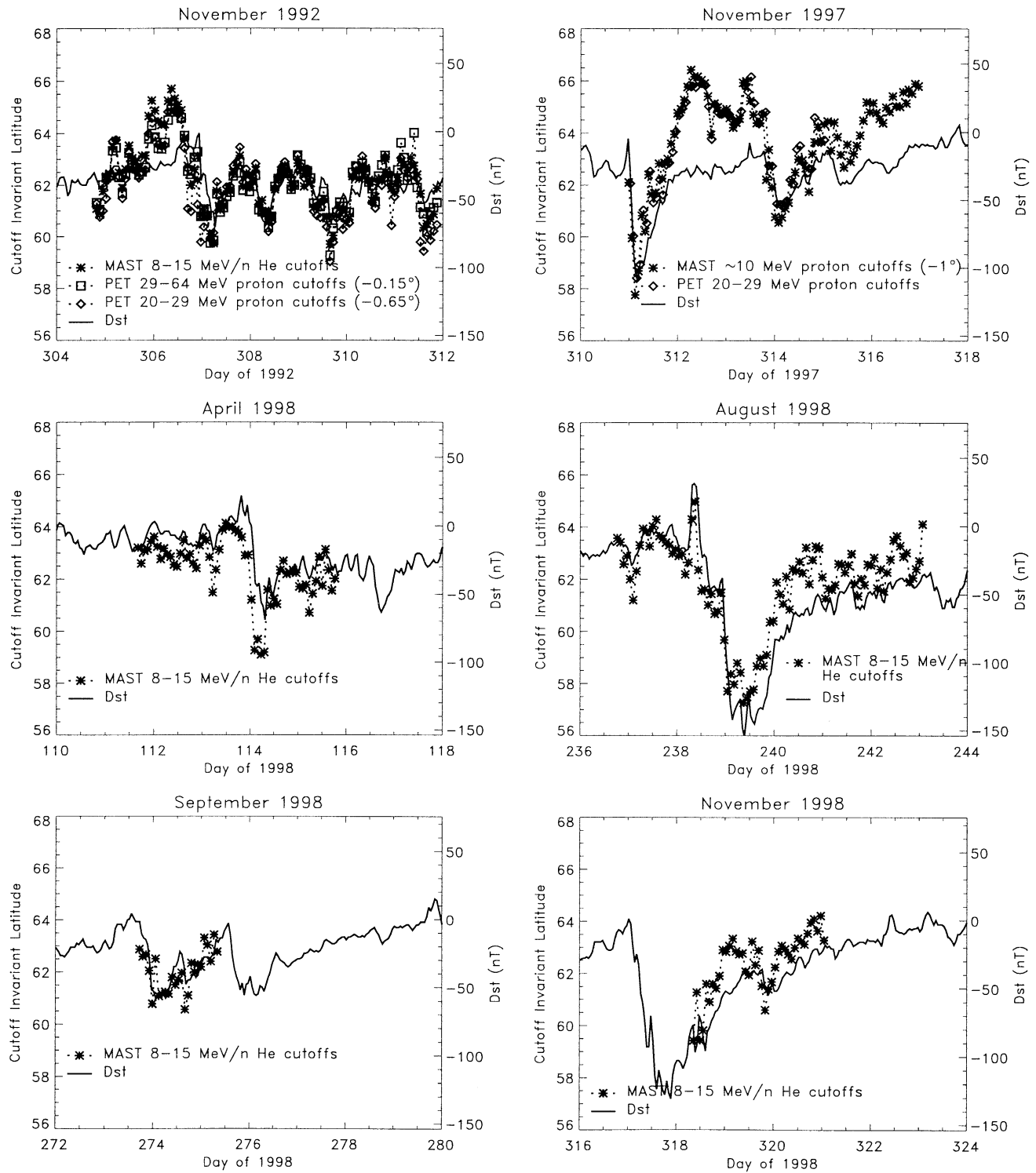


Figure 3. Orbit-averaged cutoff invariant latitude (left-hand scale) as a function of time during the six time periods, measured using the rates indicated from the Proton/Electron Telescope (PET) and the Mass Spectrometer Telescope (MAST), compared to the geomagnetic activity index Dst (right-hand scale). The Dst values have been plotted at the centers of their 1-hour measurement windows.

nT during a major geomagnetic storm moves the cutoff latitude by $\sim 8^\circ$ – 10° for these ~ 8 – 15 MeV/nucleon He nuclei (which have a rigidity of ~ 250 – 340 MV, equivalent to ~ 30 – 60 MeV protons). There is some suggestion of a downward curvature at high values of Kp

in Figure 6, perhaps suggesting that linear extrapolation in Dst is better than in Kp to estimate the effects of larger storms, but without additional measurements under more extreme conditions it is difficult to be certain.

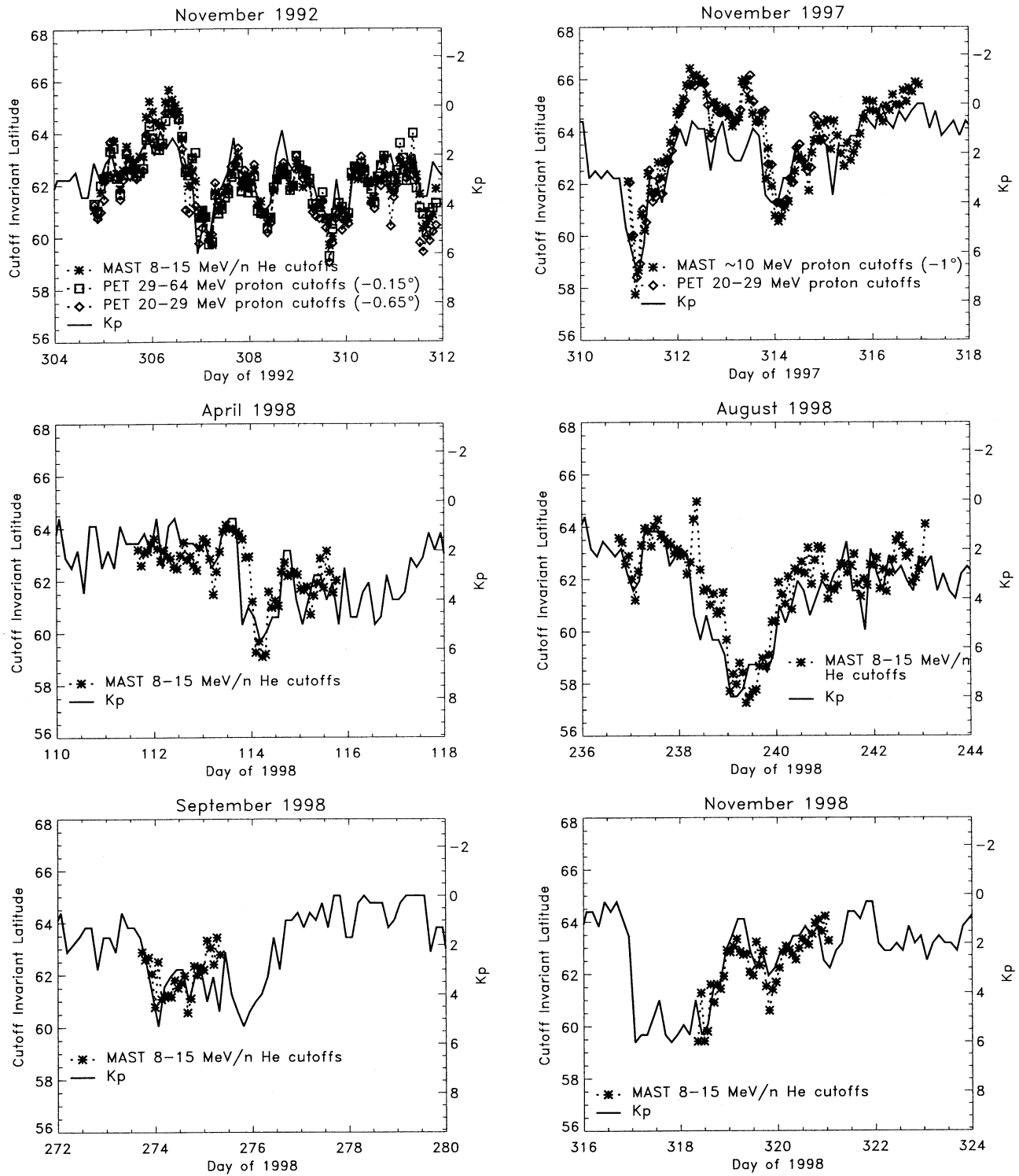


Figure 4. Orbit-averaged cutoff invariant latitude (left-hand scale) as a function of time during the six time periods, measured using the rates indicated, compared to the geomagnetic activity index Kp (right-hand scale). The Kp values have been plotted at the centers of their 3-hour measurement windows.

3.2. Cutoff Variations With Local Time

In order to examine the local time dependence of the cutoff, the cutoff latitude at each of the four crossings per orbit was corrected to first order for variations in Dst by subtracting $Dst/19.11$, effectively extrapolating to the cutoff location at $Dst=0$. A polar plot of the

residual, “corrected” invariant latitude for the MAST Z2 rate versus magnetic local time (MLT) is shown in Figure 7. Crossings over both poles were treated separately, and an offset circle was fit in each case. The resulting fits are nearly identical in both hemispheres, with a radius of $25.85 \pm 0.04^\circ$ in the north and

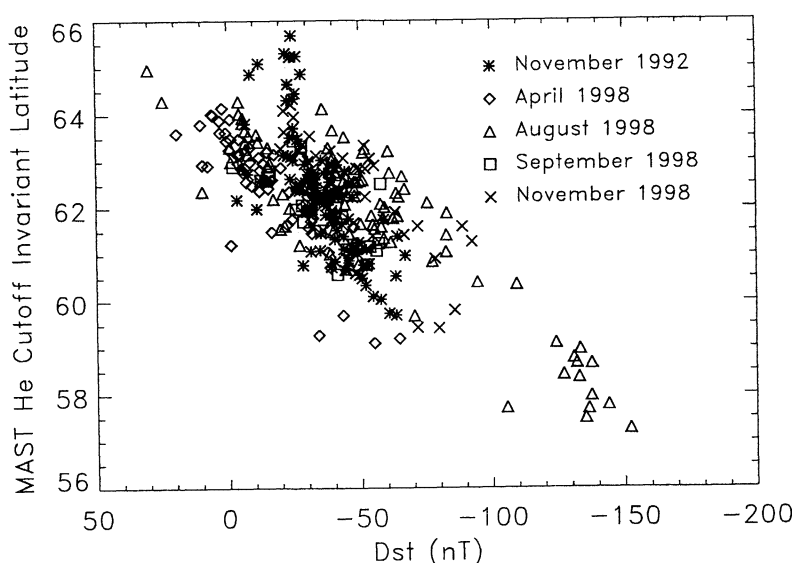


Figure 5. Orbit-averaged cutoff invariant latitude for $\sim 8\text{--}15$ MeV/nucleon He plotted versus Dst interpolated to the same time as the cutoff measurement, for the five time periods indicated.

$25.82 \pm 0.04^\circ$ in the south. The center of the northern circle is offset by $0.75 \pm 0.06^\circ$ toward 2211 ± 0018 MLT, while the southern circle is offset by $0.85 \pm 0.06^\circ$ toward 2113 ± 0016 MLT.

Superficially, Figure 7 resembles a plot of the auroral oval. It is important to remember, however, that the discrete aurora arises from low-energy particles precipitating from the magnetosphere in a relatively narrow latitudinal band, while the data points in Figure 7 mark only the boundary of an approximately circular region over the poles filled more or less uniformly with high-energy radiation during an SEP event. Nevertheless, since the extent and position of the auroral oval are routinely determined, and since its variabil-

ity has been studied for a long time [e.g., *Feldstein and Starkov*, 1967] using a variety of ground-based and space-based techniques [e.g., *Sheehan and Carovillano*, 1978; *Gussenhoven et al.*, 1983; *Whalen et al.*, 1985, and references therein], it is of some interest to compare auroral and cutoff measurements. As it turns out, there are a number of important differences between the aurora position and the boundary of access of higher-energy particles to low Earth orbit which would need to be accounted for if one were to try to deduce the location of the energetic particle cutoffs from auroral measurements.

At the energies and altitudes considered here, the extent of the SEP particles is not limited to the region of

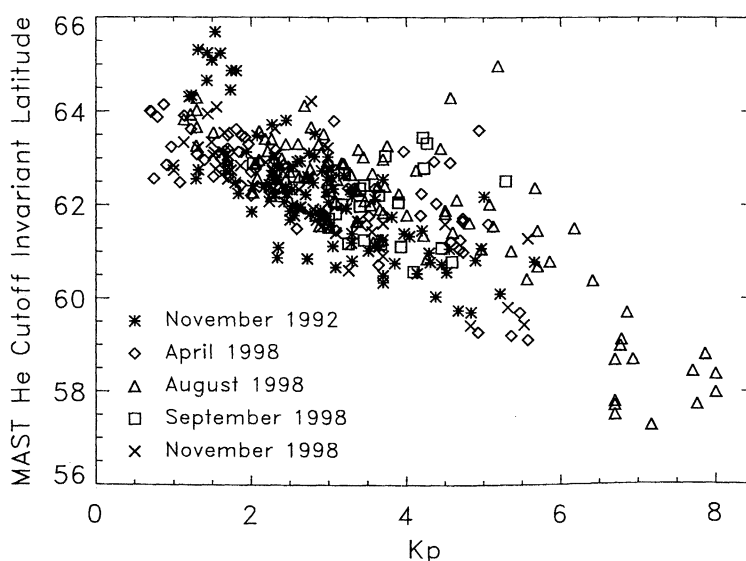


Figure 6. Orbit-averaged cutoff invariant latitude for $\sim 8\text{--}15$ MeV/nucleon He plotted versus Kp interpolated to the same time as the cutoff measurement, for the five time periods indicated.

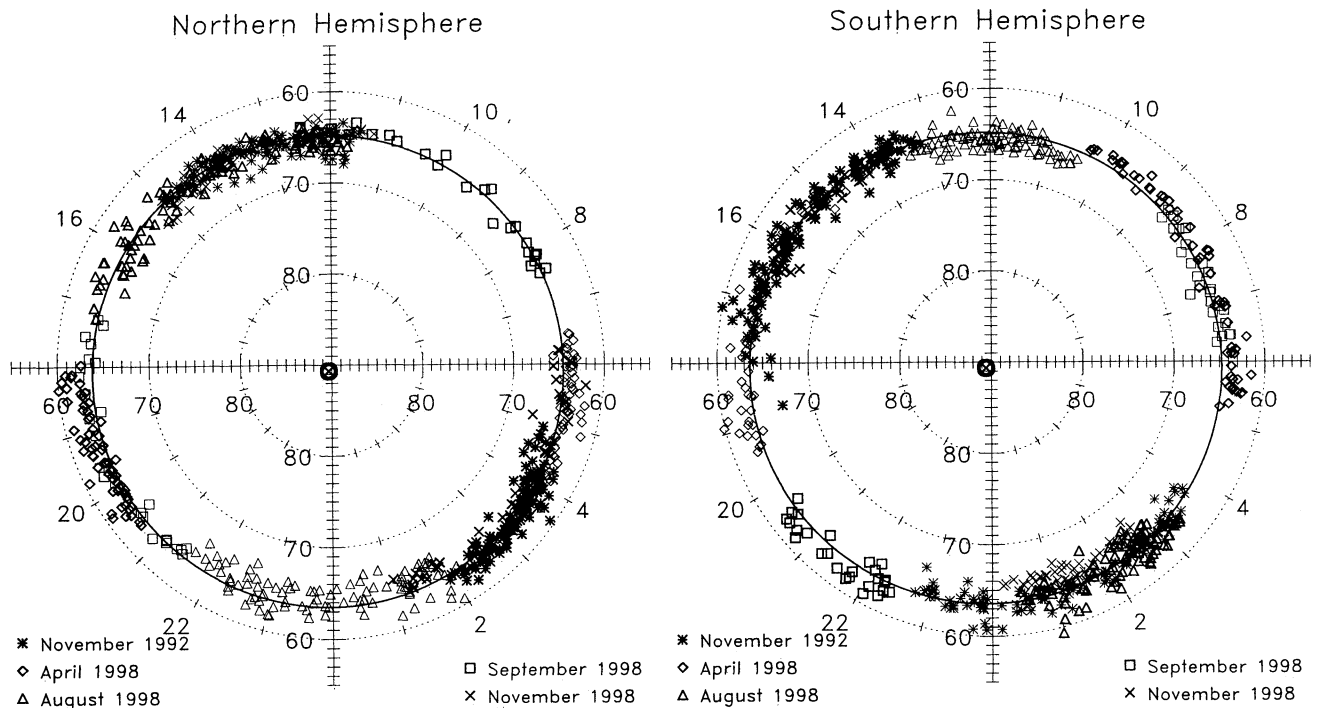


Figure 7. Polar plot of individual cutoff crossings for $\sim 8\text{--}15$ MeV/nucleon He during the time periods indicated, in invariant latitude versus magnetic local time (MLT). Each invariant latitude value has been adjusted to account for *Dst*-correlated variations (see text). For each symbol type, the darker symbols are for crossings entering the polar cap, while the lighter ones are for exiting the polar cap. For each pole the circled cross marks the center of the offset circle fit to the data.

open field lines but rather extends several degrees below it, resulting in a larger circle than that encompassed by the auroral oval. Even considering the aurora's equatorward boundary, *Gussenhoven et al.* [1983] find the radius of the auroral oval to be 21.2° when $Kp = 0$, offset by 2.4° , using < 20 keV precipitating electrons (which have rigidities < 0.14 MV). This is a significantly smaller circle than the one of $\sim 26^\circ$ radius we find for the SEP cutoffs, with a much larger offset than the $\sim 0.8^\circ$ found here. Likewise, the electron polar cap boundary has been found to be offset by $\sim 5^\circ$ during quiet times, with a radius of $\sim 18^\circ$ [e.g., *Evans and Stone*, 1972]. The direction of the offset is also different for the auroral oval and the energetic particle cutoffs. *Gussenhoven et al.* [1983] show that the center of the circle is shifted toward 0240 MLT, nearly 90° away from the direction found from the particle cutoffs both here and by *Fanselow and Stone* [1972].

The difference in size of the cutoff circle we find here and that of the auroral oval appears reasonably consistent with our earlier work on the relation between cutoff latitude and rigidity [*Leske et al.*, 1996], where during moderately disturbed periods we found $\sim 3^\circ\text{--}4^\circ$ difference between the cutoff for ~ 300 MV particles and that extrapolated to 0 MV particles, corresponding to the open field line boundary. Also, the smaller offset for the higher-rigidity He agrees with earlier measurements of the local time dependence of proton cutoffs at similar

rigidity [e.g., *Fanselow and Stone*, 1972], where a variation of $< 2^\circ$ was found with local time (corresponding to an offset of the circle center by half of that, or $< 1^\circ$).

Although a simple offset circle does a reasonable job of fitting the data in Figure 7, there is clearly a significant scatter about the circle, with a standard deviation somewhat greater than 1° . In some cases, large excursions in latitude were found for only one of the four cutoff crossings, as illustrated in Figure 8. Here the cutoffs measured on individual crossings are plotted versus time. In most cases the individual curves track each other well. The ordering of the tracks and the spread of $\sim 2^\circ$ between them are generally consistent with the direction and size of the offset found in Figure 7. However, on day 307 of 1992 and days 113, 238, and 239 of 1998, one (or at most two) of the four traces deviate to higher latitudes than the rest, sometimes by nearly 6° ; a similar deviation to lower latitudes is seen on day 114 of 1998. Comparison with Figure 3 shows that these excursions track *Dst* fairly closely in all cases. We have not examined anything other than global geomagnetic indices as indicators of geomagnetic activity, but clearly during these cases some process not longitudinally symmetric must be taking place. All of the observed high-latitude deviations take place on the dayside, between ~ 0720 and 0920 MLT in April 1998 and between ~ 1100 and 1300 MLT in both November 1992 and August 1998, suggesting a possible associa-

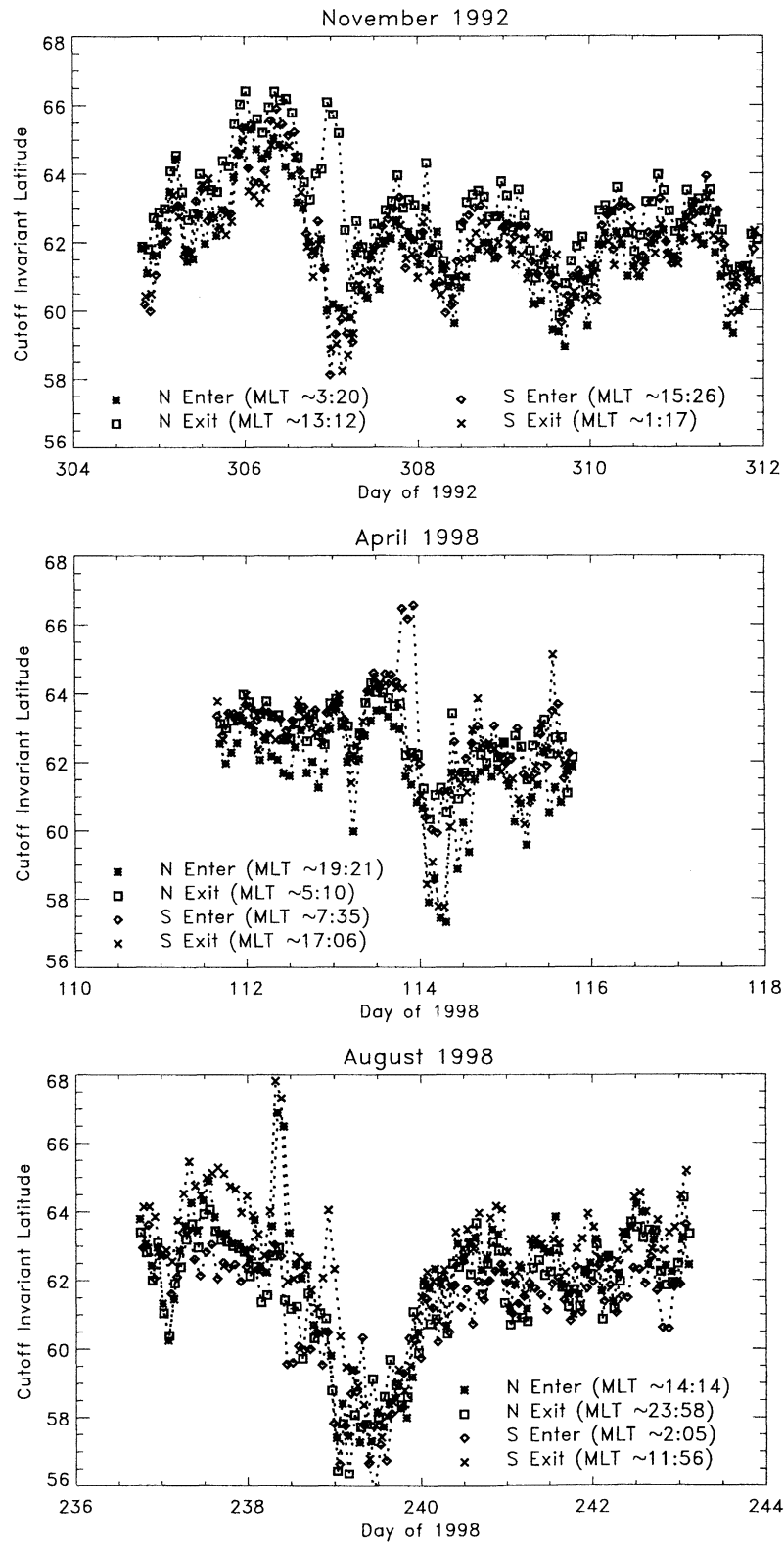


Figure 8. Cutoff invariant latitude of ~ 8 -15 MeV/nucleon He for each of the four crossings per orbit as a function of time, for the three time periods where large deviations were found at one of the crossings. The listed values of MLT are the average values for each crossing; the spread was typically several hours (see Figure 7).

tion with the cusp region. Fortunately, for the purposes of predicting times of low geomagnetic cutoff latitudes, most of these events appear to result in locally higher (and thus less hazardous) cutoff latitudes, though the

low number of observed occurrences makes it impossible to draw general conclusions. Given the unknown nature of these events and the large size of the excursions, further study is warranted.

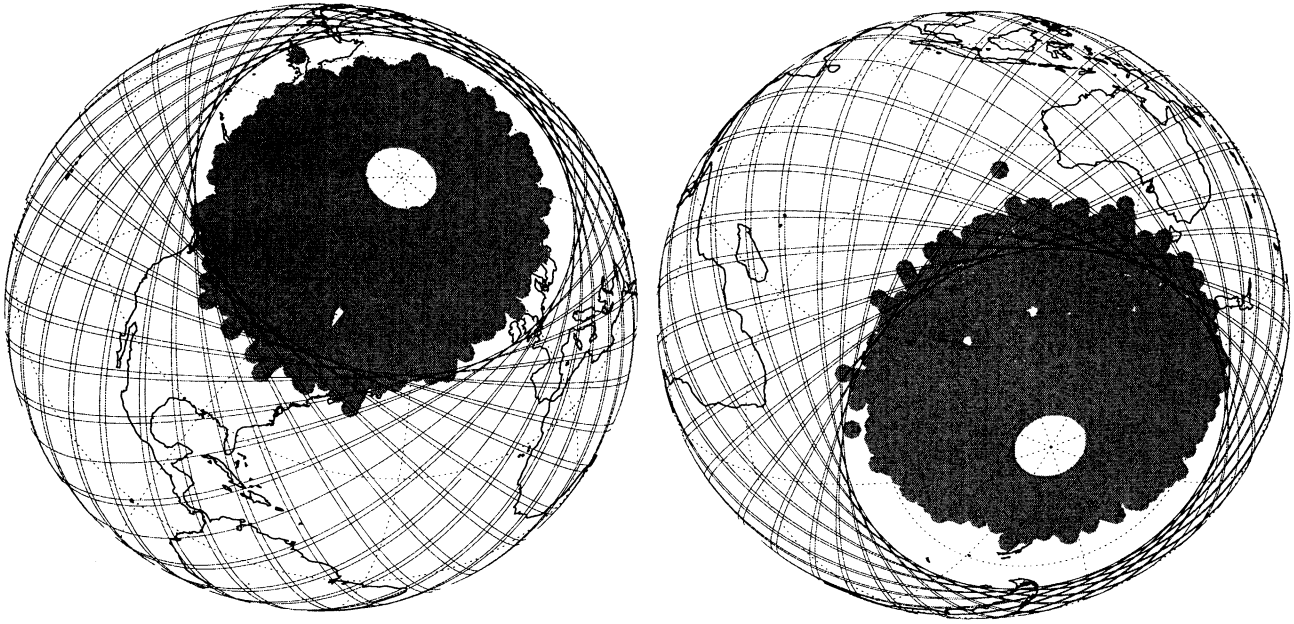


Figure 9. The location of > 16 MeV/nucleon oxygen events (shaded circles) observed by MAST during the October/November 1992 SEP events, compared to the International Space Station (ISS) ground track (thin line), as in the work of *Leske et al.* [1997]. Events due to anomalous cosmic ray oxygen trapped in the radiation belts [*Cummings et al.*, 1993] were omitted from this plot.

4. Implications for the Space Station

In its 51.6° inclination orbit the International Space Station (ISS) is well shielded by the magnetosphere from solar energetic particles most of the time, as shown in Figure 9. Figure 9 shows the calculated approximate ground track for the ISS orbit compared to the location of > 16 MeV/nucleon oxygen events observed by MAST during the November 1992 SEP events. The median energy of these nuclei is ~ 22 MeV/nucleon, which has the same rigidity as 110-MeV protons if the oxygen charge state is $+7$ [*Leske et al.*, 1996]. The ISS orbit crosses the nominal boundary of the polar cap region only at certain longitudes. During a large SEP event the radiation dose in this polar region can far exceed that in the radiation belts, posing a potential risk to both astronauts and their equipment. Since the ISS orbit is nearly tangential to the polar cap, the amount of time the Station spends in the polar cap potentially exposed to solar particles is very sensitive to the location of the cutoff.

We performed a straightforward calculation to estimate the effect of cutoff variations on the radiation dose received at the ISS orbit; the results of this calculation are shown in Figure 10. For simplicity, the Space Station orbit was taken to be circular at 400-km altitude and 51.6° inclination about a spherical Earth. The invariant latitude shown in the top panel of Figure 10 was calculated along this orbit using the IGRF 1995 field model with the BILCAL program (available from the National Space Science Data Center (NSSDC) at

<http://fdg.gsfc.nasa.gov/IGRF.html>). For illustration purposes we assume that the geomagnetic cutoff for 30-MeV protons is constant for a day at either the nominal cutoff value (left side of Figure 10), suppressed by 5° from nominal (middle), or suppressed by 15° (right side).

Assuming the SEP protons have a differential energy spectrum represented by a power law with an index of -3 , and using an empirically derived cutoff-rigidity relation [*Leske et al.*, 1996], we calculate the total fluence of > 30 MeV protons as a function of time illustrated in the middle panel of Figure 10 for the three cutoff conditions. This fluence has been normalized to be equal to unity after a day at the nominal cutoff. We have selected a threshold of 30-MeV protons since their range is $\gtrsim 4$ mm in aluminum, which is sufficient to penetrate all parts of an astronaut's space suit and even the walls of the space shuttle middeck [*Siscoe et al.*, 2000]. Also, the rigidity of 30-MeV protons is similar to that of 8 MeV/nucleon He nuclei, facilitating comparisons to our cutoff measurements. Note that a cutoff suppression of only 5° below its nominal location, as we often observe (Figure 3), increases the average exposure time of the Station by more than a factor of 2.5, while a 15° suppression would increase the exposure by more than a factor of 8. While we have not actually observed a suppression as great as 15° , we have not had the opportunity to study periods with Dst below about -150 either. Linear extrapolation (which may not be warranted) from Figure 5 suggests that a cutoff suppression of 15° might be associated with a geomagnetic storm

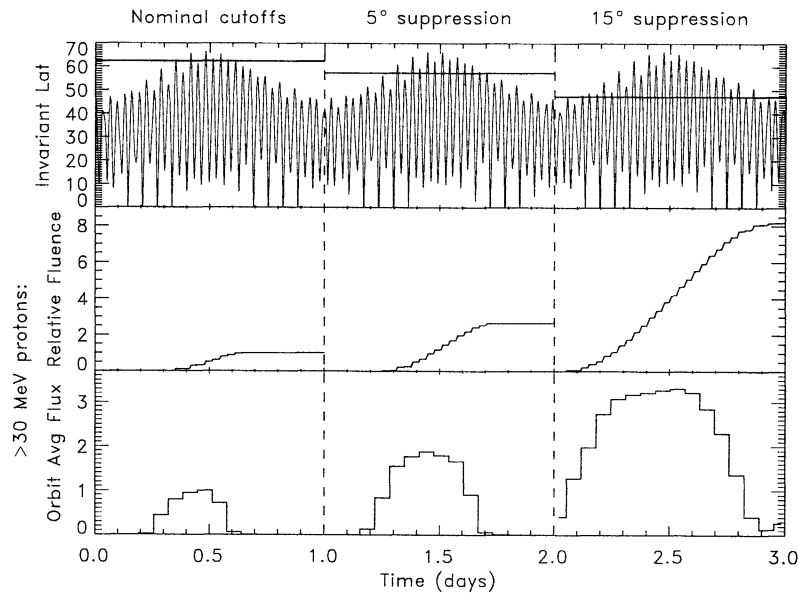


Figure 10. Calculated quantities plotted versus time for the ISS orbit, assuming nominal cutoffs (left), 5° cutoff suppression (center), or 15° cutoff suppression (right). (top) Assumed cutoff superposed on invariant latitude for ISS orbit. (middle) Fluence of > 30 MeV protons, normalized to unity after one day at nominal cutoffs. (bottom) Orbit-averaged flux of > 30 MeV protons at the ISS orbit, normalized to unity for the highest-intensity orbit under nominal conditions.

with Dst around -300 . In the bottom panel of Figure 10 we show the orbit-averaged flux of > 30 MeV protons, normalized to a maximum of unity for the nominal cutoff case. Both the flux per orbit and the number of orbits exposed to > 30 MeV protons increase as the cutoff suppression becomes greater, with some high-energy protons seen on every orbit with a 15° suppression.

The calculations in Figure 10 were based on stable cutoffs for an entire day, so that all longitudes would be sampled and the average effect of the cutoff could be determined. For cutoff variations of less than one day duration, the amount of increased radiation exposure at the Space Station, if any, depends critically on the maximum invariant latitudes reached by the Station during the suppression. For example, a suppression of 5°, if limited to a half-day duration, would have little or no effect if it occurred when the Station never reached extreme invariant latitudes (i.e., if centered at day = 1.0 in Figure 10). Conversely, if the same suppression started just as the Station reached high latitudes (such as around day = 1.2 in Figure 10), the full effect would be felt.

Timing of the cutoff suppression relative to the peak intensity of the SEP event itself also plays an important role in the total dose received at the ISS. A loose correlation has been reported between the calculated size of the polar cap and the intensity of solar particles [Siscoe *et al.*, 2000]. Some such correlation should naturally be expected, since the shocks driven by coronal mass ejections which trigger the largest geomagnetic storms (which are more directly responsible for the size of the polar cap) and the solar energetic particles themselves

both originate in solar active regions. An active region often produces several events during the two weeks it takes to rotate across the solar disk, and the shock from one event may coincide with the peak intensity of another. Such a superposition can be seen in the November 1992 and 1997 events studied here by comparing the time of peak intensity of the second of each pair of these events in Figure 1 to the minimum cutoffs in Figure 3. Also, in addition to geomagnetic storms and associated cutoff suppressions, shock events themselves can produce large, locally accelerated particle increases. During the month-long period from late September to late October 1989, which contained a series of very large SEP events, more than half the radiation dose received by cosmonauts aboard Mir arrived during a single ~ 10 hour interval when a high intensity of shock-accelerated particles coincided with a large geomagnetic storm (G. Badhwar, private communication, 1996).

Regardless of the intensity of the SEP event itself, Figure 10 shows that an additional large factor of radiation exposure may arise owing to the suppression of the cutoff. Thus, while solar observations or upstream particle detector monitors might allow predictions of arrival time and intensity of an approaching coronal mass ejection or shock event [e.g., Cohen *et al.*, this issue], the response of the magnetosphere could change the anticipated radiation dose at the Space Station by nearly an order of magnitude and should be independently measured or predicted.

Real-time evaluation of the geographical size and shape of the region accessible to SEPs has recently become a high priority for the ISS program [Siscoe *et al.*,

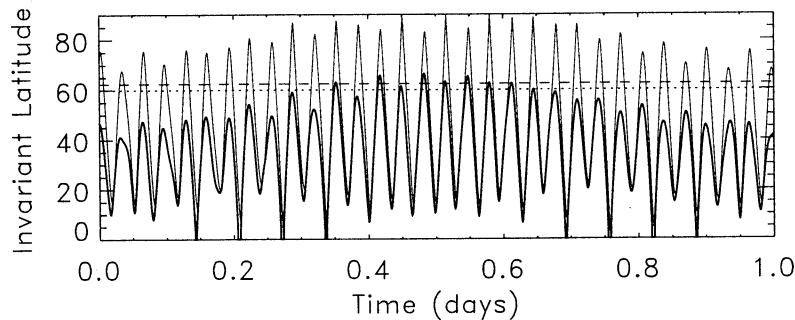


Figure 11. Calculated invariant latitude versus time for the ISS (thick curve) and the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) (thin curve) when the relative phases of the orbits are such that both satellites reach high latitudes at the same time. The nominal average cutoffs for 30-MeV protons (dashed line) and 100-MeV protons (dotted line) are also shown.

2000]. A polar-orbiting spacecraft such as SAMPEX which crosses the caps on each orbit could be used to determine the cutoff location four times per orbit, or about once every 15–30 min, during high rate periods. If the data were telemetered in real time, such a monitor could often provide a warning of up to several hours to the Space Station of a cutoff suppression in progress, since only several ISS orbits per day cross into the polar caps (Figures 9 and 10). Even during those times when the phase of the ISS and SAMPEX orbits relative to latitude are the same, the fact that SAMPEX enters the polar cap on every orbit means that the polar region will have been sampled at most a half orbit before the ISS is vulnerable, as can be seen in Figure 11. A cutoff suppression which commences while the ISS is at high latitudes, however, would not be detected with any advance warning using this approach.

5. Summary and Conclusions

The location of the geomagnetic cosmic ray cutoff varies constantly, often by more than 5° in less than one day for particles with the same rigidity as 30-MeV protons. This variation is very clearly correlated with geomagnetic activity as measured by indices such as Dst . However, the correlation with Dst is worse at certain times, often during critical periods such as the onset of a geomagnetic storm when a large cutoff suppression can occur hours before the corresponding change in Dst . This suggests that one should be cautious about using Dst as a proxy for cutoff variations in lieu of direct measurements. Although Kp may correlate better than Dst with the cutoff during some of these periods, it is worse than Dst during others. From the standpoint of an operational space weather warning system, even if accurate forecasts of both Dst and Kp were available, it is unclear how one would choose which of the two to use at any given time to best predict the cutoff location.

Usually, the residual cutoff variability after correcting for Dst -correlated variations is relatively independent of local time for these energetic particles, amounting to

$\lesssim 2^\circ$ throughout the day. However, large local deviations are occasionally found. These should be studied further before deciding that a single-point assessment of the polar cap size, based on either globally averaged geomagnetic indices or direct particle measurements, is really adequate for evaluating ISS radiation hazards.

With the uncertainty in accurately assessing the cutoff location from geomagnetic activity, it is desirable to obtain actual particle measurements of the cutoff location to aid in forecasting the ISS radiation environment. Such measurements are relatively easy to make, given a particle detector in a polar orbit and a sufficiently high particle counting rate with adequate time resolution, assuming the data are rapidly available. A small sample of rates from a single orbit is, in fact, transmitted from SAMPEX once or twice a day in near real time, at a reduced time resolution of 192 s. It may be possible to increase the time resolution to the ~ 15 s or less required to measure the cutoff latitude to an accuracy of $\sim 1^\circ$, at least for a few key rates, if the onboard data processing unit [Mabry *et al.*, 1993] were reprogrammed. Additional real-time data dumps would be required, at least during forecast periods of high solar activity, which might be accomplished using relatively inexpensive, autonomous ground stations. Thus it may be possible to use SAMPEX as a test bed to develop a cutoff suppression early warning system.

Acknowledgments. This work was supported by NASA under contract NAS5-30704 and grant NAGW-1919. GOES data, Dst , and Kp indices were obtained from the National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce, through the Space Environment Center and the National Geophysical Data Center.

Janet G. Luhmann thanks Henry Garrett and Ron Turner for their assistance in evaluating this paper.

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(Received June 30, 2000; revised August 25, 2000; accepted September 14, 2000.)